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ABSTRACT

This module expands on the introductory discussion of nitrogen in other modules. The various chemical forms of nitrogen found in land treatment systems are defined. Inputs from waste application as well as natural sources are quantified for typical situations. A discussion of nitrogen transformations in the soil includes mineralization and immobilization processes (organic-inorganic transformations). The importance of carbon to nitrogen ratio of applied waste is emphasized in determining what reactions will occur in the soil. Possible losses and removals of nitrogen from a land treatment system are discussed. All of the above factors are combined into a mass balance in determining wastewater and sludge loadings, on a nitrogen basis, for typical situations. Data on nitrogen loadings and removals from various existing systems are summarized in the final section of the module. An illustration of short-term nitrogen loading calculation, using the decay series concept, is presented in the Appendix. (Author/EE)

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Land Application

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The objective of this program is to increase the knowledge of engineers, scientists, waste management specialists and other practitioners in the concepts and principles needed to properly utilize the potential of land for the application of wastes. It is designed for individuals concerned with waste disposal alternatives for municipal, industrial, and agricultural wastes. The modules in this Program incorporate knowledge from sanitary and environmental engineering, agronomy, soil science, agricultural engineering, economics, and law.

The program consists of some twenty-five modules and audio-visual materials as appropriate.

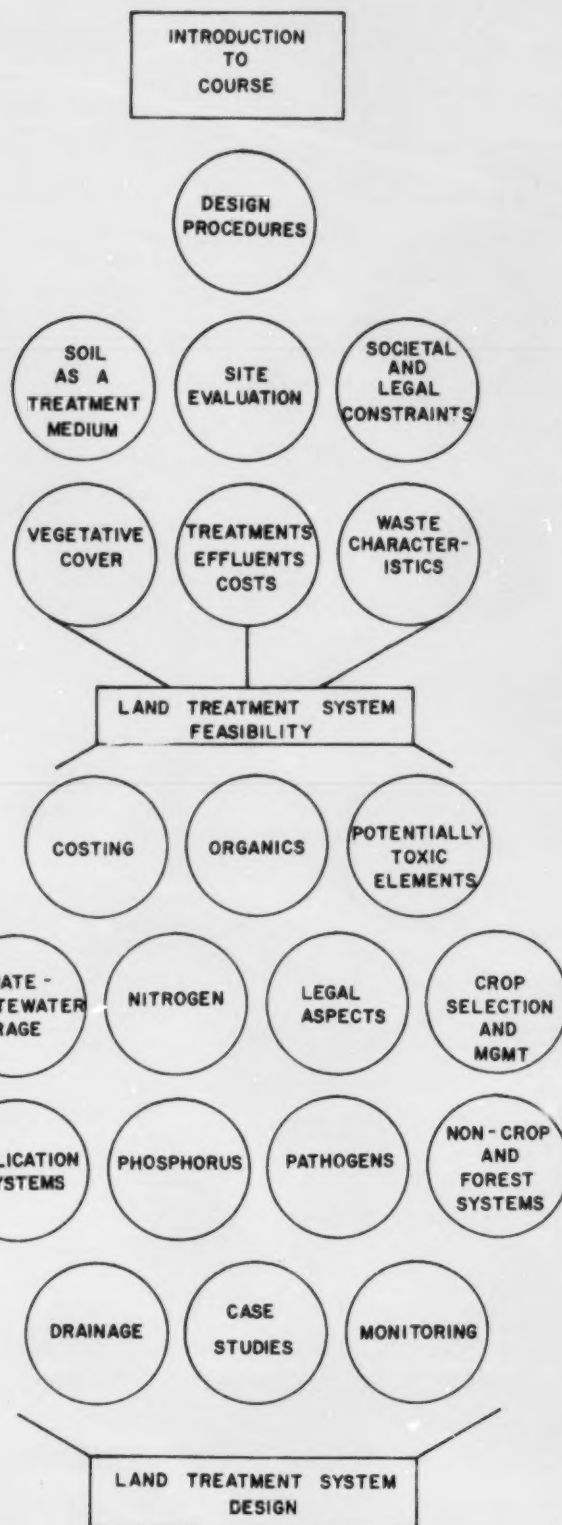
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NITROGEN CONSIDERATIONS

Module 15

January, 1978

Summary

This module expands on the introductory discussion of nitrogen in Level I modules 3, "Soil as a Treatment Medium"; 7, "Role of Vegetative Cover"; and 5, "Waste Characteristics".

The various chemical forms of nitrogen found in land treatment systems are defined. Inputs from waste application as well as natural sources are quantified for typical situations. A discussion of nitrogen transformations in the soil includes mineralization and immobilization processes (organic-inorganic transformations). The importance of carbon to nitrogen ratio of applied waste is emphasized in determining what reactions will occur in the soil. Possible losses and removals of nitrogen from a land treatment system are discussed. All of the above factors are combined into a mass balance of nitrogen. Examples illustrate the application of this mass balance in determining wastewater and sludge loadings, on a nitrogen basis, for typical situations.

Data on nitrogen loadings and removals from various existing systems are summarized in the final section of the module. Other modules have pointed to nitrogen as the most prevalent limiting factor for waste addition to a given site. This module reiterates that point, while presenting detailed discussion of the components of the nitrogen interactions, or mass balance, of a system and demonstrating the application of this concept to typical systems.

An illustration of short-term nitrogen loading calculation, using the decay series concept, is presented in the Appendix.

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Glossary

ammonification - The biochemical process whereby ammoniacal nitrogen is released from nitrogen-containing organic compounds.

denitrification - The biochemical reduction of nitrate and nitrite to gaseous nitrogen either as molecular nitrogen or as an oxide of nitrogen.

evapotranspiration - The combined loss of water from a given area during a specified period of time, by evaporation from the soil and plant surfaces and by transpiration from plants.

immobilization - The conversion of an element from the inorganic to the organic form in microbial or plant tissues, thus rendering the element not readily available to other organisms or other plants.

leaching - The removal of materials in solution from the soil.

mineralization - The conversion of an element from an organic form to an inorganic state as a result of microbial decomposition.

nitrification - The biochemical oxidation of ammonium to nitrate.

nitrogen fixation - The conversion of elemental nitrogen (N_2) to organic combinations or to forms readily utilizable in biological processes; especially by certain bacteria in the nodules of leguminous plants, making the nitrogen available to the plants.

volatilization - The process of vaporizing or becoming gaseous.

Objectives

Upon completion of this module, the participant should be able to:

1. List the six forms of nitrogen of importance in land treatment.
 - a. Indicate which are in gaseous form.
 - b. Indicate which is (are) subject to leaching to the groundwater.
 - c. Indicate which can be tied up by the soil cation exchange complex.
2. Name three sources of nitrogen input to a land treatment site.
3. Discuss the effect of C:N ratio of organic matter on immobilization and mineralization. Give the approximate cut-off point, in terms of % N or C:N, at which immobilization or mineralization should predominate.
4. List five possible mechanisms for nitrogen loss and removal from a land treatment site. Discuss the conditions necessary for each of these factors.
5. State the generalized nitrogen mass balance equation in descriptive terms, and illustrate its mathematical application to the calculation of nitrogen loading.

Introduction

The most important factor limiting land application of wastes is often the amount of inorganic nitrogen contained or released from wastewater and sludges. Large inputs of nitrogen, while stimulating plant growth, can lead to increased losses to ground and surface waters. Such increases may result in excessive growth of algae and aquatic weeds. Moreover, a build-up of nitrate in drinking water supplies is thought to pose a health hazard to humans, particularly infants, as well as livestock. Maintenance of the groundwater nitrogen level below the drinking water standard of 10 mg/l $\text{NO}_3\text{-N}$ requires careful management. Management decisions on nitrogen loading rates must be based on a thorough knowledge of the various forms of nitrogen contained in wastes, their properties, the transformations which occur in soils, and the rates associated with these transformations.

In order to maintain permissible levels of nitrogen in groundwater, land application site operators must know the various forms of nitrogen in wastes, their properties, the transformations which occur in soils, and the rates associated with these transformations.

The major forms of nitrogen of importance in waste management are briefly outlined below.

Organic nitrogen is bound in carbon-containing compounds such as proteins. Within the soil, organic-N, a constituent of humus, is not available for direct plant uptake, but is slowly transformed to available forms by means of microbial decomposition. The nitrogen-containing organic compounds are often abbreviated R-NH_2 .

Ammoniacal nitrogen includes two forms, the ammonium ion (NH_4^+) and gaseous ammonia (NH_3). Ammonium, by virtue of a net positive charge, can be held in the soil on clay and organic matter cation exchange sites. Ammonium is utilized by both plants and microorganisms as a nitrogen source. Ammonia gas exists in equilibrium with the ammonium ion. At high pH values (> 8.5) ammonia predominates and may escape into the atmosphere in significant quantities.

Nitrite (NO_2^-) is a highly mobile anion formed in soils as an intermediate during the microbial conversion of ammonium to nitrate (see below). Nitrite is generally transitory in soils but may accumulate under certain conditions; it is toxic to higher plants in very small quantities.

Nitrate (NO_3^-) is a highly mobile anion, readily utilized by both plants and microorganisms. Nitrate is of primary interest in waste application systems since it may be readily leached from the soil and, when present in excess in drinking water, is thought to be a health hazard to humans. The U.S. Public Health Service has recommended a drinking water standard of not more than 10 mg/l $\text{NO}_3\text{-N}$. The term $\text{NO}_3\text{-N}$ is read nitrate-nitrogen and refers only to the nitrogen portion of the nitrate anion. Do not confuse NO_3^- with $\text{NO}_3\text{-N}$ as they are separate entities.

The form of nitrogen of most concern in land application of wastes is nitrate since it may be readily leached from the soil.

$$10 \text{ mg/l } \text{NO}_3\text{-N} = 44.3 \text{ mg/l } \text{NO}_3^-$$

$$2.26 \text{ mg/l } \text{NO}_3\text{-N} = 10 \text{ mg/l } \text{NO}_3^-$$

Nitrous oxide (N_2O) is a gaseous form only slightly soluble in water. It is a normal constituent of the atmosphere in small quantities (< 1 ppm), and is probably not utilized by plants. Nitrous oxide is formed during the denitrification of nitrate.

Molecular nitrogen (N_2) is a gaseous form comprising nearly 80% of the normal atmosphere. Like nitrous oxide, molecular nitrogen is an end product of denitrification.

Nitrogen Behavior in Terrestrial Systems

The various forms of nitrogen are interconnected through a series of complex transformations, which collectively constitute the nitrogen cycle. For purposes of this discussion, the nitrogen cycle will be divided into three portions: inputs, organic-inorganic transformations, and losses or removals (Figure 1).

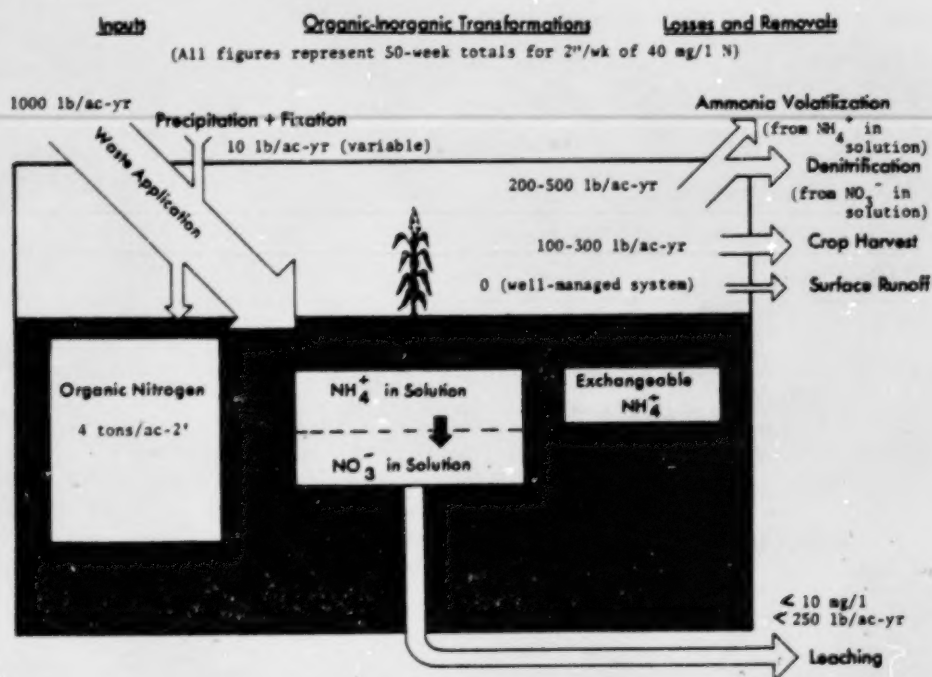


Figure 1. Nitrogenous materials are subject to a series of complex transformations in the soil. These transformations, mediated by microorganisms, environmental factors, and management practices, determine the ultimate fate of nitrogen inputs in terrestrial systems.

Nitrogen Enters System Through Wastes, Precipitation, Atmosphere

Inputs: Nitrogen enters terrestrial systems in waste-water and/or sludge applications, natural precipitation (rain and snow), and through fixation of molecular nitrogen from the atmosphere by specialized microorganisms.

Wastewater and Sludge: Municipal wastewaters and sludges contain variable amounts of nitrogen in the forms of organic-N, ammonium-N, and nitrate-N. Some representative values and common loading rates are presented in Table 1. The data in this table should immediately raise some questions. As was noted in Module 3, "Soil as a Treatment Medium" and Module 7, "Vegetative Cover" the annual nitrogen removal by crops seldom exceeds 300 lb/acre. Low rate applications of wastewater (2 inches/week for 30 weeks) add approximately this amount while higher rates considerably exceed this value. The addition of a small amount of sludge (1 acre-inch) may also exceed 300 lb/acre of nitrogen. Thus, with moderate to high application rates of either effluent or sludge, strict nitrogen control will require management methods other than or in addition to crop uptake.

Moderate to high application rates of sludge and wastewater require management beyond a reliance on crop uptake.

Table 1. Total nitrogen content in various wastes and common annual loading to land.

Waste	Total N	Annual N loading to land	
	mg N/l	Assume 20 mg N/l	
		Low Rate ¹	High Rate ²
		-----lb/acre-yr-----	
Sewage Effluent			
Untreated	20-85		
Primary	20-50	270	2840
Secondary	10-40		
		Assume 5% N (dry wt.) ³	
Sewage Sludge	1-8% (dry wt.)	450	

¹ Assumes application rate of 2"/week for 30-week period (representative of irrigation and overland flow systems)

² Assumes application rate of 6"/day for 14 days followed by 14-day rest period over a 30-week season (representative of rapid infiltration system).

(continued on next page)

Table 1. (continued)

³Assumes one annual application of liquid sewage sludge (96% moisture; 4% solids) in amount of one acre-inch

Sources: Larson et al., 1973; Menzies, 1973; Pound and Crites, 1973; Reed et al., 1972

Precipitation: Annual additions of nitrogen in precipitation generally occur in the nitrate and ammoniacal forms. Amounts fluctuate markedly depending on season, climate, and surrounding industrial activity. Within the U.S., precipitation inputs vary from 1-15 lb N/acre-yr (Sepp, 1971).

Nitrogen input from rain and snow varies from 1 to 15 pounds per acre a year.

Nitrogen Fixation: Specialized bacteria which develop in the roots of legumes and certain other plants are capable of "fixing" atmospheric nitrogen; that is, they can convert molecular nitrogen into a form usable by plants. This mutually beneficial relationship between microorganisms and plants is termed symbiosis. Where appropriate plants are present, symbiotic nitrogen fixation may range from approximately 50 to 300 lb N/acre-yr. A certain amount of non-symbiotic fixation also occurs through the activity of free living microorganisms, and can contribute from 20 to 100 lb N/acre-yr (Brady, 1974). There is evidence that nitrogen fixation is much reduced by the presence of readily available nitrogen from other sources such as waste additions. Nitrogen fixation may therefore constitute only a minor input on land receiving waste applications.

Nitrogen input from nitrogen-fixing bacteria is minor on land receiving waste applications.

Waste Additions Affect Organic-Inorganic Transformations of Nitrogen in Soil

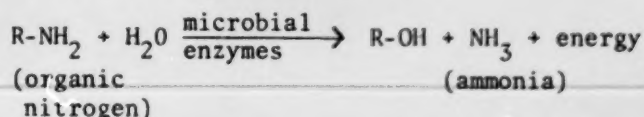
The amount of native nitrogen present in soils ranges from approximately 2,000-15,000 lb/acre, much of which is concentrated in the surface layers. Most of this nitrogen is bound in organic forms and is neither available to plants nor for leaching. Decomposition of organic matter by soil microorganisms slowly transforms organic-N to inorganic forms, a process termed mineralization.

Most native nitrogen in soils is bound in organic forms; it is unavailable to plants and will not leach to groundwater.

The reverse of mineralization, that is, the transformation from inorganic-N to organic forms, is called immobilization.

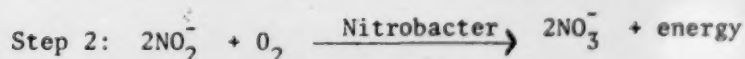
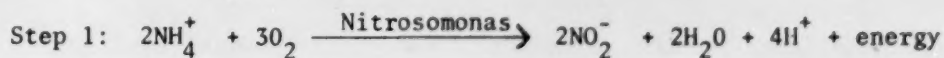
Mineralization: The general term mineralization covers a whole series of reactions, the most important of which are ammonification and nitrification.

Ammonification is the conversion of organic nitrogen to ammonia as shown below.



This reaction can be carried out by a wide variety of microorganisms.

Within the pH range of most soils (i.e. 4.5-7.5), ammonia exists as the ammonium ion (NH_4^+). This positively charged ion may react with the cation exchange complex in the soil. Because of competition with other cations such as calcium (Ca^{+2}), magnesium (Mg^{+2}), and potassium (K^+), however, only about 5% of the cation exchange capacity is available for ammonium adsorption (Lance, 1972). For soil with a CEC of 15 meq/100 g, this results in an ammonium adsorption capacity of 1 g/ft² of soil, or about 100 lb N/acre. Clearly, this capacity could be saturated in a matter of months, even at low ammonium application rates. Ammonium, however, undergoes a further transformation: nitrification. Nitrification essentially regenerates the capability of the soil to adsorb ammonium ions. So far as we now know, nitrification is carried out in two steps by specialized microorganisms.



Both steps require oxygen and are thus favored in well aerated soils. Nitrification is also affected by temperature, soil moisture, and pH. At temperatures below approximately 30°F, nitrification essentially stops; the

Ammonification, which can be carried out by a variety of microorganisms is the conversion of organic nitrogen to ammonia.

The ability of the soil to adsorb ammonia is limited; only about 5% of CEC is available for such adsorption.

Nitrification regenerates the capability of soil to adsorb ammonia; it is favored by good aeration of soil, 80-90°F temperatures and a neutral to slightly alkaline pH.

optimum temperature range is between 80-90°F (Brady, 1974). The process is inhibited in very wet (poorly aerated) or very dry soils, but readily occurs at moisture levels within and slightly below the acceptable range for higher plants. Nitrification is greatest at neutral to slightly alkaline pH values and is slow in strongly acid soils. The effect of pH is probably indirect, resulting from an association with the availability of exchangeable bases such as potassium, calcium and magnesium.

Under most conditions favoring the two reactions, step 2 closely follows step 1, precluding any significant accumulation of nitrite. Large amounts of ammonia, however, as might occur when ammonified wastes are added to highly alkaline soils, are apparently toxic to step 2 organisms (Nitrobacter), resulting in a temporary build-up of nitrite which is very toxic to higher plants. Assuming near ideal temperature, moisture, and pH conditions, nitrification occurs very rapidly. Nitrate-nitrogen generation rates of from 6-22 lb/acre-day have been reported in surface soil after the addition of 100 lb/acre of ammonium nitrogen (Broadbent and Tyler, 1957).

The major significance of nitrification in waste application systems lies in the fact that a relatively immobile form (NH_4^+) is transformed into a highly mobile form (NO_3^-) which may then readily leach from the soil. Furthermore, nitrate is required for denitrification, a process to be discussed later.

Immobilization: Immobilization is essentially the reverse of mineralization, that is, inorganic nitrogen is converted into organic nitrogen as a component of microbial tissue. Immobilization occurs when the nitrogen content of decomposing organic material is insufficient to supply microbial needs. Inorganic nitrogen from the soil is then incorporated into the microbial cells.

Addition of ammonified wastes to highly alkaline soils can result in a build-up nitrite; nitrite accumulation is very toxic to higher plants.

Through nitrification immobile ammoniacal nitrogen is converted to the highly mobile form of nitrate which may readily leach from soil.

The ratio of carbon to nitrogen (C:N) in the organic matter indicates whether mineralization or immobilization of nitrogen is likely to predominate. When materials with a high C:N ratio (low nitrogen concentration) are added to soils, immobilization occurs initially. With time, however, carbon is lost as carbon dioxide (CO_2), while nitrogen is conserved. The C:N ratio thus narrows and mineralization eventually predominates. If the added organic matter has a low C:N ratio (high nitrogen concentration), mineralization occurs from the outset.

The carbon-nitrogen ratio of the organic matter in soil indicates whether organic nitrogen will be transformed to inorganic forms or the reverse will predominate.

As a general rule, mineralization occurs when the N content of the organic matter exceeds approximately 1.5% by dry weight; this corresponds to a C:N ratio of between 20 and 25. Where the N content is less than 1.5%, immobilization occurs until decomposition with accompanying carbon loss sufficiently narrows this ratio. Some representative wastes in both high and low C:N categories are presented in Table 2.

Table 2. Relative C:N status for various wastes.

LOW C:N RATIO (N content greater
than 1.5% by dry wt.)

Sewage sludges
Fresh animal feces
Some legume straws
Most young plant residues

HIGH C:N RATIO (N content less than
1.5% by dry wt.)

Vegetable cannery residues
Timber processing waste
Mature cereal straw
Some manures with included
bedding straw

When materials with a high C:N ratio are applied to soils immobilization occurs; mineralization predominates when materials with a low C:N ratio are added.

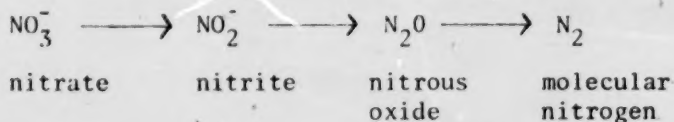
Several Mechanisms Remove Nitrogen from System

Nitrogen is lost or removed from terrestrial systems through several means including ammonia volatilization, denitrification, crop harvest, surface runoff, and leaching. Lance (1972) provides a useful review of these processes.

Ammonia Volatilization: In moist, alkaline soils, ammonium salts undergo a chemical reaction resulting in the evolution of ammonia gas (NH_3). When liquid sludge is surface applied, 60% or more of the $\text{NH}_4\text{-N}$ may thus be lost, depending on the application rate and soil properties. In general, such losses decrease with increasing clay content, and increase with application rate (Ryan and Keeney, 1975). Volatilization losses can be reduced or prevented by injecting or otherwise incorporating sludge into the soil so that ammonium can react with the soil cation exchange complex.

Denitrification: Denitrification is the process(es) whereby nitrate-nitrogen is converted into gaseous forms, N_2O or N_2 . The reactions involved may be purely chemical (chemodenitrification) or brought about by microorganisms (biodenitrification). Chemodenitrification is generally restricted to highly acid soils and will likely be of only minor significance in land application systems. Therefore, the following discussion focuses on biodenitrification.

Under anaerobic conditions, where molecular oxygen is lacking, bacteria use the chemically combined oxygen in nitrate. Nitrous oxide (N_2O) and molecular nitrogen (N_2) thus form and escape into the atmosphere; nitrous oxide generally predominates under field conditions.



The bacteria involved in these reactions require organic carbon as an energy source. Thus, to encourage biodenitrification, land application systems must be managed so as to bring nitrate and organic carbon together under anaerobic conditions. This is no simple task.

Sixty percent of ammonium nitrogen may be lost in the form of ammonia gas in liquid sludge application; incorporation of sludge into soil reduces this loss.

Biodenitrification is the conversion of nitrate into gaseous forms of nitrogen, beneficial because nitrate may be readily leached from soil to groundwater.

Land application systems must bring nitrate and organic carbon together in order to encourage biodenitrification.

Sewage effluents often contain most of their total nitrogen in organic or ammoniacal forms. Transformation of these forms to nitrate requires aerobic conditions which are not conducive to denitrification. Thus, alternate aerobic and anaerobic periods or zones must be achieved. Moreover, in many secondary effluents, the relative amounts of total N and biodegradable organic carbon are of the same general magnitude, 20-30 mg/l. The loss of carbon as CO_2 , however, often occurs at a higher rate than nitrification. This results in organic carbon removal prior to the formation of appreciable nitrate. Thus, by the time nitrogen is converted to a form that can be denitrified, much of the required organic carbon has been consumed. Approximately 0.9-1.3 grams of biodegradable organic carbon are needed to denitrify one gram of nitrate-nitrogen (Viets and Hageman, 1971). This means that if 70% of the total organic carbon is lost as CO_2 in aerobic zones, then less than 30% of the total N can be denitrified even under optimal denitrifying conditions. For these reasons, the extent of denitrification is extremely difficult to predict and generalized values are often of minimal value without on-site demonstrations using a specific waste.

Denitrification is difficult to predict because by the time nitrogen is converted to a form that can be denitrified, much of the required organic carbon has been consumed.

Crop Uptake and Harvest: Nitrogen uptake by harvestable crops constitutes a significant mechanism for N removal. Some representative values are presented in Table 3. Without harvest, the annual nitrogen uptake will simply return to the soil in an organic form. During initial years of operation, some of this nitrogen may accumulate in the soil. As soon as a new equilibrium level is reached, annual additions could be offset by annual mineralization so that no further accumulation occurs. However, data indicating N accumulation in the range of 120 lb/ac-yr over several decades of operation are available from Werribee Farm, Melbourne, Australia (Johnson, et al., 1974).

Significant amounts of nitrogen are removed by harvest of cover crop.

Table 3. Nitrogen removal by selected crops when irrigated with municipal sewage effluent

Crop	Yield per acre	N Uptake lb/acre-yr
Corn Grain	114 bu	83
Corn Silage	6.0 tons	161
Wheat Grain	54 bu	83
Reed Canarygrass (3 cuttings)	4.3-7.0 tons	272-356

Sources: Sopper and Kardos, 1973; Kardos *et al.*, 1974.

Nitrogen Loss from Surface Runoff: Surface runoff

occurs whenever water application rates exceed the soil infiltration capacity. Most states require that surface runoff be contained from land application systems. The magnitude of nitrogen loss in surface runoff is highly variable from one site to another depending on natural precipitation, topography, season, and application rates and methods. Such loss can be made minimal in a well designed and managed system.

Nitrogen loss from surface runoff can be minimized by good management of land application site.

Leaching of Nitrogen: After the water holding capacity of a soil is reached, additional water percolates through the soil. The resulting leaching losses of nitrogen are generally small in natural systems, due to limited amounts of available N. Inputs of wastewater or sludge need not result in excessive leaching loss of N where sound management is practiced. Obviously, where nitrogen inputs exceed the capacity for crop uptake and/or denitrification, leaching of nitrate must be expected. Careful assessment of nitrogen inputs versus estimated losses and removals can limit nitrate leaching to acceptable levels. "Acceptable levels" should mean that the NO_3^- -N level in groundwater under or near the land application site do not exceed 10 mg/l. The exact interpretation of this standard (*i.e.* whether the water to be sampled is the groundwater or only the leachate from the site, or whether the sampling site relates to nearby areas where groundwater

If nitrogen inputs exceed the capacity of crop harvesting and denitrification to take up nitrogen, leaching of nitrogen can be expected.

is used for drinking supply, or sampling must be performed directly under the application site) is left to the state regulatory authority involved. They must be consulted in dealing with this question.

Good Management Requires Careful Determination of Nitrogen Loading

Nitrogen Mass Balance

In any land application system, nitrogen additions must be balanced against acceptable losses and removals. Estimates of inputs and losses are thus required, and must be assessed on both a short and long term basis.

The nitrogen mass balance equation helps to determine how nitrogen additions can be balanced against losses and removals.

A nitrogen mass balance equation for a terrestrial system is presented in Table 4. Potential N inputs include waste additions, precipitation, N fixation, and mineralization of native soil nitrogen. Potential outputs consist of crop removal, leaching and runoff losses, denitrification, ammonia volatilization and net storage or accumulation of soil N. Again, the latter includes both organic and inorganic forms. Not all terms may be needed in every case nor are all terms now quantifiable for all situations.

Table 4. Nitrogen mass balance equation for terrestrial systems.

INPUTS		REMOVALS
Total N in Waste		N Removal in Crops
+		+
N in Precipitation		N Loss by Leaching and Surface Runoff
+		
N Fixation	=	+
+		Denitrification
Mineralization of Native Organic N		+
		Ammonia Volatilization
		+
		N Accumulation in Soil

In the initial few years of operation, waste application may cause a net accumulation of nitrogen in soil

organic matter or on soil colloids. Thus, not all nitrogen inputs would be accounted for in losses or removals. Net storage from one year, however, would become a potential input the following year. Failure to consider such short term accumulations can lead to an over-estimate of permissible loading rates.

Normally, additions of ammonium-N result in the rapid attainment of a new equilibrium. The cation exchange complex may be saturated during the first year or even after the first application, after which no net accumulation occurs. Accumulation of organic-N may continue for several years in the case of highly organic wastes, but eventually the microbial population will adjust so that annual mineralization equals annual additions. At this point the system has reached a new steady-state condition. The storage term in the right-hand portion of the mass balance equation (Table 4) thus equals release from storage in the left-hand portion. The two terms then cancel one another on a long term basis.

Calculation of Loading

The following discussion assumes that any short term increases in nitrogen storage in the soil have already occurred and that there are no significant additions by fixation (i.e. the cover crop is non-leguminous).¹ The mass balance equation thus reduces to:

$$\begin{array}{ccccccc} \text{Total N} & + & \text{N in} & = & \text{N Removal} & + & \text{Leaching} & + & \text{Denitri-} & + & \text{Ammonia} \\ \text{in Waste} & & \text{Precip.} & & \text{in Crops} & & \text{Loss} & & \text{fication} & & \text{Volatil-} \\ & & & & & & & & & & \text{ization} \end{array}$$

This equation can be used to calculate nitrogen loading rates for either wastewater or liquid sludge applications.

¹ Additional information regarding short-term considerations is presented in the Appendix.

Wastewater Loading: The mass balance equation may be written as:

(Equation numbers in parentheses)

$$N + \frac{cP}{4.43} = C + \frac{aQ}{4.43} + dN + vN \quad (1)$$

where:

N = total nitrogen in applied wastes (lb/acre-yr)

c = concentration of nitrogen in precipitation (mg/l)

P = precipitation (acre-in/acre-yr)

C = removal of nitrogen in crop (lb/acre-yr)

a = allowable nitrogen concentration in percolating or runoff water (mg/l)

Q = volume of water leaving site via percolation or runoff (acre-in/acre-yr)

d = fraction of N which is denitrified ($\% \times 10^{-2}$)

v = fraction of N which is volatilized as ammonia ($\% \times 10^{-2}$)

4.43 = conversion factor

The volume of water leaving the site (Q) is a function of precipitation, evapotranspiration, and wastewater additions such that:

$$Q = P + W - ET \quad (2)$$

where:

P = precipitation

W = wastewater additions

ET = potential evapotranspiration

(assumes that P + W will allow potential ET to be realized in all cases)

(acre-in/acre-yr)

Furthermore, for wastewater containing a total nitrogen concentration y (mg/l):

$$N = \frac{yW}{4.43} \quad (3)$$

Therefore:

$$\frac{yW}{4.43} + \frac{cP}{4.43} = C + \frac{a(P + W - ET)}{4.43} + \frac{d(yW)}{4.43} + \frac{v(yW)}{4.43} \quad (4)$$

Solving for wastewater application (W):

$$W = \frac{4.43 C + a(P - ET) - cP}{y - a - y(d + v)} \quad (5)$$

The following assumptions and conditions are suggested for general usage of equation 5:

1. Ammonia volatilization (v) is set equal to zero unless known to be otherwise.
2. Denitrification (d) is also set equal to zero. This is a failsafe approximation and can be relaxed only on the basis of on-site demonstrations or future research findings.
3. The allowable nitrogen concentration in runoff and percolating water (a) is set equal to the Environmental Protection Agency recommended $\text{NO}_3\text{-N}$ drinking water standard, 10 mg N/l.
4. Crop removal (c) is set equal to a constant for a given crop. There will be some variability among years which may at times result in the runoff or percolate water containing more nitrogen than the recommended standard. The same will occur in years when the precipitation is below average.
5. The annual excess of nitrogen is assumed to be dissolved in the total annual excess of water, that is, without seasonal highs and lows.
6. The net effect of conditions 4 and 5 is that some water leaving the site may at times contain nitrogen in excess of the 10 mg/l standard. This condition should be clearly understood and some agreement reached with regulatory agencies as to what is or is not acceptable. Careful monitoring will be required to substantiate the overall performance of the system. The conservative nature of condition 2 may partially offset the vagaries of conditions 4 and 5. These conditions provide a very conservative approach to the N loading calculation. They should be evaluated according to the principles outlined in this module and elsewhere, and relaxed if conditions warrant at a particular site, for example

when the design provides for conditions conducive to ammonia volatilization or denitrification.

The following two examples are included to illustrate the use of these equations in calculating the acceptable loading rates for wastewater.

PROBLEM #1 (Wastewater Loading)

- A. GIVEN: An area in the northeastern U.S. with an average annual precipitation of 35 inches and a potential evapotranspiration of 20 inches. Determine how much sewage effluent, containing 20 mg/l total N, can be applied so that the soil leachate will average ≤ 10 mg/l $\text{NO}_3\text{-N}$. Assume that reed canarygrass, harvested from the site, will remove 250 lb/acre-yr and that precipitation contains an average of 0.5 mg N/l.

SOLUTION: by equation 5 and suggested conditions for usage

$$W = \frac{4.43 (250) + 10 (35 - 20) - 0.5 (35)}{20 - 10}$$

$$= 124 \text{ acre-in/acre-yr}$$

Note: by equation 3, total N applied would equal 560 lb/acre-yr.

- B. Suppose the application season equals 30 wk/yr. Determine the weekly liquid loading needed to dissipate 124 acre-in/acre-yr.

SOLUTION:

$$\frac{124 \text{ acre-in/acre-yr}}{30 \text{ wk/yr}} = 4.1 \text{ acre-in/acre-wk}$$

Note: This value must be compared with the hydraulic capabilities of potential sites to see if it is acceptable.

- C. Assuming that 4.1 acre-in/acre-wk is compatible with the hydraulic properties of potential sites, how many acres would be required for a 1 mgd wastewater flow?

SOLUTION:

$$1 \text{ mgd} = 365,000,000 \text{ gal/yr}$$

$$1 \text{ acre-in} = 27,154 \text{ gal}$$

$$\begin{aligned} \text{acreage} &= \frac{365,000,000 \text{ gal/yr}}{(4.1 \text{ acre-in/acre-wk})(27,154 \text{ gal/acre-in})} \\ \text{requirement} &= 108 \text{ acres} \end{aligned}$$

Note: This value represents effective land application area; storage areas, buffer zones, etc. will be additional.

PROBLEM #2 (Wastewater loading)

- A. Given: Same conditions as in problem #1 except a semi-arid area where annual precipitation equals 20 inches and annual potential evapotranspiration equals 20 inches. Determine effluent loading on both an annual basis and a weekly basis; determine the acreage required.

SOLUTION:

$$W = \frac{4.43 (250) + 10 (20 - 20) - 0.5 (20)}{20 - 10}$$

$$= 110 \text{ acre-in/acre-yr}$$

By equation 3, this amounts to 496 lb N/acre-yr. Assuming a 30-wk application season, the weekly application rate is:

$$\frac{110 \text{ acre-in/acre-yr}}{30 \text{ wk/yr}} = 3.67 \text{ in/wk}$$

For a 1 mgd flow, the acreage requirement is:

$$\frac{365,000,000}{(110)(27,154)} = 122 \text{ acres}$$

Compare the answers in this problem with those obtained for Problem #1. The lower allowable loading rate in Problem #2 is due to the decrease in precipitation as compared to evapotranspiration, resulting in a lower dilution factor for nitrate in percolating wastewater.

Liquid Sludge Loading:(Equation numbers
in parentheses)

$$N + \frac{cP}{4.43} = C + \frac{aQ}{4.43} + dN + vN$$

(1)

where:

N = total nitrogen in applied wastes (lb/acre-yr)

c = concentration of nitrogen in precipitation (mg/l)

P = precipitation (acre-in/acre-yr)

C = removal of nitrogen in crop (lb/acre-yr)

a = allowable nitrogen concentration in percolating
or runoff water (mg/l)Q = volume of water leaving site via percolation or
runoff (acre-in/acre-yr)d = fraction of N which is denitrified (% x 10⁻²)v = fraction of N which is volatilized as ammonia (% x 10⁻²)

4.43 = conversion factor

The volume of water leaving the site (Q) is a function of precipitation, evapotranspiration, and the water added in liquid sludge such that:

$$Q = P + zW - ET$$

(6)

where:

P = precipitation

W = liquid sludge additions

acre-in/acre-yr

ET = potential evapotranspiration

z = moisture fraction in liquid sludge (% x 10⁻²)

Furthermore,

$$N = \frac{(t)(s)10^6 W}{4.43}$$

(7)

where:

t = total N fraction in waste (% of solids x 10⁻²)s = total solids (% x 10⁻²)

Therefore:

$$\frac{ts(10^6)W}{4.43} + \frac{cP}{4.43} = C + \frac{a(P + zW - ET)}{4.43} + \frac{dts10^6 W}{4.43} + \frac{vts10^6 W}{4.43}$$

(8)

Solving for liquid sludge application (W):

$$W = \frac{4.43 C + a(P - ET) - cP}{ts10^6 - az - ts10^6 (d + v)}$$

(9)

The same conditions suggested for the use of equation 5, apply to the use of equation 9.

The following example is included to illustrate the use of these equations in calculating the acceptable loading rates for liquid sludges.

PROBLEM #1 (Liquid sludge loading)

A. GIVEN: An area in the northeastern U.S. with an average annual precipitation of 35 inches and a potential evapotranspiration of 20 inches; a liquid sludge with the following characteristics: 96% moisture, 4% solids, 3% total nitrogen (dry solids basis).

Determine how much liquid sludge can be applied so that the soil leachate will average $\leq 10 \text{ mg/l NO}_3\text{-N}$. Assume that a grass crop on the site will remove 250 lb N/acre-yr, and that precipitation contains an average of 0.5 mg N/l.

SOLUTION: by equation 9 and suggested conditions for usage:

$$W = \frac{4.43 (250) + 10 (35 - 20) - 0.5 (35)}{(.03) (.04) 10^6 - 10 (.96)}$$

$$= 1.04 \text{ acre-in/acre-yr}$$

Note: by equation 7, total N applied would then equal 282 lb/acre-yr.

Existing Land Application Systems Provide Data on Nitrogen Loading

Irrigation

Wastewater spray irrigation systems have commonly used application rates ranging from 1-3 inches per week. With secondary effluents, corresponding quantities of nitrogen are of the same general magnitude as crop requirements over the growing season. Under these application rates, only small amounts of nitrogen are lost through leaching.

Only small amounts of nitrogen are lost through leaching in most spray irrigation systems using secondary effluent.

Table 5 presents a partial nitrogen mass balance for six years of operation of a spray irrigation field under hay cover. Nearly all of the applied nitrogen can be accounted for in the harvested reed canarygrass. When crop removals and estimated leaching losses are combined, however, they exceed the N content of applied wastewater. The excess presumably resulted from precipitation inputs, fixation of atmospheric nitrogen, and/or mineralization of native organic nitrogen. The latter source was likely the major contributor.

Table 5. Partial nitrogen mass balance for a wastewater irrigation site under reed canarygrass cover in Pennsylvania. Secondary effluent was applied at a rate of 2"/week on a year-round basis. Values in the table are annual averages over a 6-year period.

	INPUTS	=	REMOVALS	
Annual Average				Annual Average
lb/acre-yr				lb/acre-yr
354	Total N in Waste		N Removal in Crops	345
	+		+	
	N in Precipitation		N Loss by Leaching	75
	+		+	
	N Fixation		Denitrification	
	+		+	
	Mineralization of Native Organic N		Ammonia Volatilization	?
			+	
			N Accumulation in Soil	

Source: Sopper and Kardos, 1973.

Overland Flow

Rates of wastewater application and nitrogen loading in existing overland flow systems are roughly similar to irrigation systems. The principal mechanisms for nitrogen renovation include crop removal and denitrification, often followed by dilution upon discharge into surface waters. Renovation efficiencies, whether on a nitrogen mass or concentration basis, are typically high. Two examples are presented in Tables 6 and 7.

Nitrogen renovation is high in most overland flow systems, the principal mechanisms being crop removal and denitrification.

Table 6 data result from the application of secondary sewage effluent. On a mass basis, nitrogen removal equals nearly 83 percent. This appears to be due mostly to crop uptake; it is not clear, however, how much native N became available during the application period. Therefore, N loss due to denitrification is probably underestimated.

Table 6. Partial nitrogen mass balance for an overland flow system under reed canarygrass cover. Experimental flats (10' x 5' x 7.5"; 2% slope) received secondary effluent at a rate of 2.5 inches/week over a 12-week period.

INPUTS		=	REMOVALS	
12-wk total lb/acre				12-wk total lb/acre
137	Total N in Waste ¹		N Removal in Crops	104
	+		+	
	N in Precipitation		N in Runoff ²	23
	+		+	
?	N Fixation		Denitrification	
	+		+	
	Mineralization of Native Organic N		Ammonia Volatilization	at least 10
			N Accumulation in Soil	

¹ Applied wastewater contained the equivalent of 60 lb organic-N/acre, 51 lb ammonium-N/acre, and 26 lb nitrate-N/acre

² Runoff water contained the equivalent of 14 lb organic-N/acre, 3.5 lb ammonium-N/acre, and 5.5 lb nitrate-N/acre

Source: Hoepfel et al., 1974.

Table 7 shows results from the year-round application of raw comminuted sewage. The data do not allow construction of a mass balance, although on a concentration basis, N renovation percentages are quite high. The observed winter decrease in overall removal efficiency was likely due to decreased rates of nitrification and denitrification as well as the reduction in plant requirements.

Table 7. Nitrogen relationships for summer (May-Sept.) and winter (Nov.-Apr.) periods in an overland flow system in Ada, Oklahoma. The experimental plots, 36' x 118' with 2-4% slope, supported native grasses; raw comminuted sewage was applied at a rate of 3.9 in/wk.

	SUMMER		WINTER	
	mg/l	lb/acre	mg/l	lb/acre
NITROGEN IN APPLIED WASTE				
Org-N	5.8	111	5.8	131
NH ₄ -N	17.0	326	17.0	385
NO ₃ -N	0.8	15	0.8	18
TOTAL-N	23.6	452	23.6	534
NITROGEN IN RUNOFF				
TOTAL-N	2.2		6.8	
% RENOVATION ON CONCENTRATION BASIS	91		71	

Source: Thomas et al., 1974.

Rapid Infiltration

Rapid infiltration systems generally utilize high rates of wastewater application with the major portion of the effluent moving to groundwater at some depth or distance. To the extent that nitrogen renovation occurs before entering the groundwater, it must be due chiefly to denitrification since nitrogen additions often far exceed vegetation requirements. Additional apparent renovation results from dilution in the groundwater. With the kinds of data now available from currently operating systems, it is very difficult to differentiate between denitrification and dilution effects.

In rapid infiltration systems, nitrogen renovation occurs chiefly through denitrification; some apparently results from dilution in the groundwater.

A system in Lake George, N.Y. applies approximately 65-100 acre-feet of wastewater annually to deep sand beds. This amounts to between 3000 and 4600 lb N/acre-yr. Apparent nitrogen renovation varies considerably depending on sampling location and season. Winter values, based on samples from shallow wells in the immediate vicinity of the sand filter beds, show a high NO_3^- -N concentration of up to 21 mg/l (Aulenbach et al., 1975). This amounts to a renovation efficiency of about 25 %. In a seepage area some 200 feet away from the filter beds, however, NO_3^- -N concentrations in all seasons fall below the 10 mg/l drinking water standard. Further reduction, apparently through dilution occurs when the leachate enters West Brook before flowing into Lake George. According to Aulenbach et al., (1975), "in most instances, the nitrate-nitrogen content of West Brook exceeded recommended limits of 0.3 mg/l for control of excess algal growth. However, because of the cold water and the low phosphorus content of the stream, no problems of excessive algal growth have occurred in West Brook itself."

Wastewater application at Flushing Meadows, near Phoenix, Arizona, ranges from 300-400 acre-feet per year giving an annual nitrogen load of between 24,000 and 32,000 lb/acre-yr. Nearly 90% of the nitrogen in the original wastewater occurs as ammonium. System management relies on alternate wetting and drying cycles in an attempt to maximize denitrification. Under short flooding and drying periods of two days each, aerobic soil conditions seemed to predominate. The highly ammonified effluent thus underwent nearly complete nitrification, resulting in low ammonium-N but consistently high nitrate-N (≈ 20 mg/l) levels in the percolating water. Subsequently, wetting and drying periods were extended to two weeks each. This schedule resulted in the appearance of nitrate-N peaks of up to 71 mg/l in the leachate a few days after the start of each successive wetting period (Figure 2). Apparently, added ammonium was retained in the surface soil by cation exchange reactions during the wetting cycle. The ammonium was then nitrified during drying periods and

flushed into the groundwater early in the next flooding cycle. As the alternate two-week cycles were continued, however, ammonium concentration in the percolating water gradually increased, while nitrate behavior remained essentially unchanged. Apparently incomplete nitrification during drying cycles led to a gradual ammonium saturation of the cation exchange complex. Increasing amounts of applied ammonium were thus subject to leaching. Because of these results, Bouwer (1973) has suggested that long wetting-drying cycles (e.g. 2 weeks each) should be periodically alternated with shorter cycles (e.g. 2 days each) to increase aerobic conditions and "rejuvenate" the exchange complex in terms of ammonium retention. Other alternatives include lower loading rates and/or periodic, long rest periods of several weeks to allow complete drying of the upper soil layers.

In rapid infiltration systems long wetting-drying cycles of 2 weeks each alternated with shorter cycles of 2 days each have been suggested to increase aerobic conditions and aid in ammonium retention.

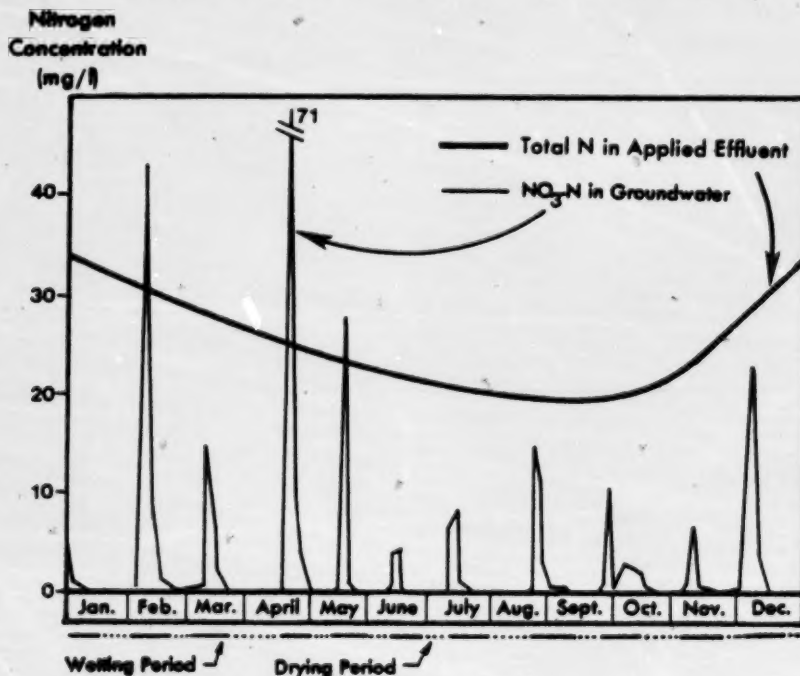


Figure 2. The high-rate application of ammonified effluent, under alternate wetting and drying cycles, results in periodic pulses of nitrate release to the groundwater. Following each pulse, the nitrate concentration in the leachate falls off sharply yielding highly renovated wastewater (after Bouwer, 1973).

The presence of high nitrate pulses has also been shown in other wastewater application studies (Lance, 1972) and offers some interesting management alternatives. For example, winter application of ammonified effluent could result in efficient removal of nitrogen as long as the adsorption capacity of the soil is not exceeded. In the spring, when warmer temperatures promote biological nitrification, periodic high nitrate concentrations in the soil leachate should be expected. Essentially, the original wastewater nitrogen has been concentrated in a relatively small volume of leachate. The bulk of leachate moving between the pulses is low in nitrogen. Recovery of the nitrified leachate pulses through underdraining or strategic well placements will likely be mandatory. Upon collection, however, this water can be recycled to croplands for its nitrogen fertilizer value. Two and one-half acre-feet of wastewater containing 30 mg/l of NO_3^- -N would supply about 200 lb N/acre for a demanding crop such as reed canarygrass; this amount of wastewater is equivalent to 1 acre-in/week over a 30 week period. If it is not possible to utilize water for crop irrigation, an inexpensive method of renovation may be to recycle it back to a point in the system where the presence of organic carbon would allow for denitrification.

Where high nitrate pulses are a problem, the nitrified leachate pulses should be recovered through underdraining or strategic placement of wells.

Barrierred Landscape System Maximizes Denitrification

An experimental system, termed a Barrierred Landscape Water Renovation System (BLWRS), is being tested at Michigan State University (Erickson *et al.*, 1972). As shown in Figure 3, it consists of a mound of soil underlain by an impervious polyvinyl water barrier. The thin bed of limestone or slag on top of the mound removes phosphorus. The aerobic zone allows for organic matter decomposition and nitrification of ammonium. The downward movement of nitrified effluent, however, is stopped by the water barrier and forced to move laterally in the anaerobic zone immediately above the barrier. Denitrification in this zone is stimulated by adding a readily degradable carbon source such as crushed grain. Renovated water then moves off the edge of the water barrier and

through deeper soil layers to the water table. Such a system can maximize denitrification, even under relatively low wastewater application rates. The nitrogen removal potential was demonstrated with liquid swine waste (Figure 3), but remains to be tested for domestic wastewaters.

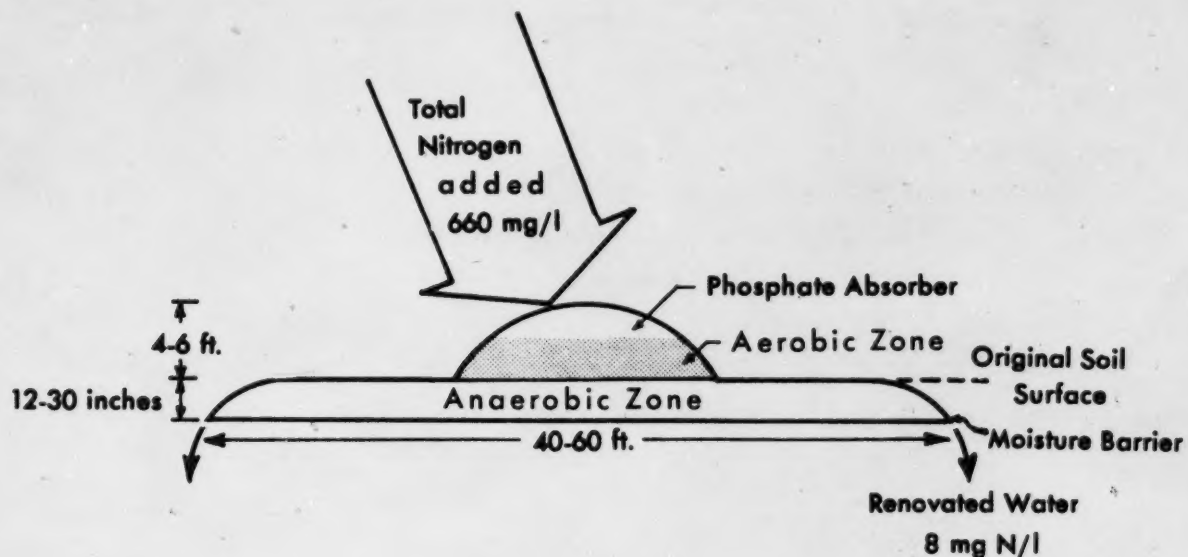


FIGURE 3. The Barriered Landscape Water Renovation System (BLWRS), developed at Michigan State University, provides a means for maximizing denitrification of nitrogenous wastes. Applications of liquid swine waste, equivalent to about 9500 lb N/acre, have resulted in highly renovated water (after Erickson *et al.* 1972).

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Appendix

Determination of Short-Term Nitrogen Loading

During the initial years of waste application, particularly with sludges, organic-N may accumulate in the soil. Since organic-N must mineralize before it is available for crop uptake or appreciable leaching, the rate of mineralization determines the rate of organic-N application.

Annual rates of mineralization are often expressed as a series of fractional mineralization for a given application and residuals from previous applications. Such a series is referred to as a decay series. For example, a decay series of .10, .05 has been suggested for municipal sewage sludges (Brown, 1975). Thus, for a given application, 10% of the organic-N is mineralized during the first year, and 5% of the residual (that which was not mineralized previously) is mineralized the second and all subsequent years until complete transformation has occurred. The same approach can be applied individually to successive yearly applications.

A decay series represents annual rates of mineralization expressed as a series of fractional mineralization for given applications and residuals from previous applications.

Suppose 100 lb/acre of organic-N were applied for each of three years. Using the above mentioned decay series, the amount of N mineralized the first year would be:

$$N_{(1)} = .10 (100) = 10 \text{ lb/acre}$$

with 90 lb/acre remaining as a residual. During the second year, another 10 lb/acre would mineralize from the new application plus 5% of the residual from the first year. Therefore,

$$N_{(2)} = .10 (100) + .05 (90) = 10 + 4.5 = 14.5 \text{ lb/acre}$$

with a 90 lb residual from the second year application and an 85.5 lb/acre residual from the first year.

During the third year:

$$N_{(3)} = .10 (100) + .05 (90) + .05 (85.5) = 18.8 \text{ lb/acre}$$

The above calculations constitute a "constant input" approach. However, in land application systems, the major concern is to maintain a constant output, consistent with crop requirements and acceptable leaching losses. A further consideration exists in that

sewage sludges will generally contain inorganic-N (mostly in the ammoniacal form) in addition to organic-N. On a practical basis, all of the inorganic-N will become available during the year of application.

Consider a liquid sludge with the following characteristics:

$$.96 = z = \text{moisture fraction } (\% \times 10^{-2})$$

$$.04 = s = \text{total solids fraction } (\% \times 10^{-2})$$

$$.03 = t = \text{total N } (\% \text{ of solids } \times 10^{-2})$$

$$.017 = i = \text{inorganic-N } (\% \text{ of solids } \times 10^{-2})$$

$$.013 = o = \text{organic-N } (\% \text{ of solids } \times 10^{-2})$$

This sludge is to be applied in an area with an average annual precipitation (P) of 35 inches and potential evapotranspiration (ET) of 20 inches. A corn crop on the site will take up approximately 100 lb/acre-yr (C); nitrogen input via precipitation is 0.5 mg/l (c). We want to determine the allowable application of liquid sludge so as not to exceed 10 mg/l NO_3^- -N (a) in the leachate. Further assume that the sludge will be injected so as to eliminate any ammonia volatilization (v) and that denitrification (d) is not known, and thus is set equal to zero as a safety factor. From equation 9 in a previous section,

$$W = \frac{4.43 C + a (P - ET) - cP}{t s 10^6 - az}$$

However, this equation was derived for long-term conditions where no net accumulation of organic-N is occurring. Under short-term conditions:

$$W_1 = \text{application during first year (acre-in/acre-yr)}$$

$$t_1 = \text{N available during first year } (\% \text{ of solids } \times 10^{-2})$$

$$= (i) + (o) M_1$$

where M_1 = mineralization rate during first year (i.e. first term of decay series).

Therefore:

$$W_1 = \frac{4.43 C + a (P - ET) - cP}{i s 10^6 + o s 10^6 M_1 - az}$$

Solving for the given waste and site characteristics:

$$W_1 = \frac{4.43 (100) + 10 (35 - 20) - 0.5 (35)}{(.017)(.04) 10^6 + (.013)(.04) 10^6 (.10) - 10 (.96)}$$

$$= 0.8 \text{ acre-in/acre during the first year}$$

Note: by adapting equation 7, this amounts to

$$N_1 = \frac{t_1 s 10^6 W}{4.43} = 132 \text{ lb N/acre}$$

To maintain a constant output of available N, however, less sludge can be applied in successive years due to mineralization of residual organic-N. Figure 4 shows the reduction in annual sludge application needed to maintain a constant output of 132 lb/acre-yr. Projected results for two application methods are illustrated. Where sludge is injected into the soil, preventing ammonia volatilization, the required reduction amounts to about 30-50% over the initial 5-10 years. For surface applications, assuming 100% ammonia volatilization, a 10-fold reduction is projected because mineralization of accumulated residuals becomes the dominant source of plant-available nitrogen.

The results in Figure 4 emphasize the necessity for analysis of inorganic versus organic nitrogen, as well as the effects of surface versus injected application. Note also that after the initial years of application, the calculated amounts tend to level off, approaching a new steady state over the long-term.

However, even for sludges with characteristics similar to those shown in Figure 4, the calculated loadings cannot necessarily be extrapolated to all sludge application sites. The decay series used for this example (i.e. .10, .05) constitutes a general estimate for a particular climate, in this case Ohio (Brown, 1975). Pratt *et al.* (1973) have suggested a decay series of .35, .10, .05 for liquid sludge applications in California. Still another series (.15, .06, .04, .02) is suggested for Wisconsin (Keeney *et al.*, 1975). Further differences will likely occur in other areas since the parameters which determine mineralization rates are strongly influenced by climatic as well as soil conditions.

Sludge Applications
Tons (Dry Solids)/Acre-yr.

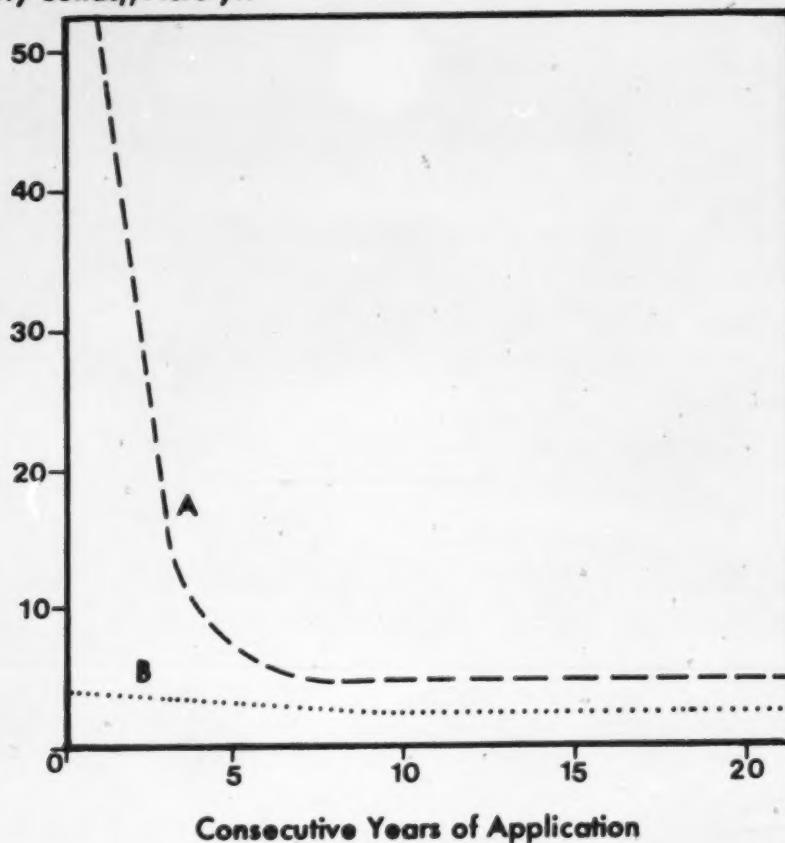
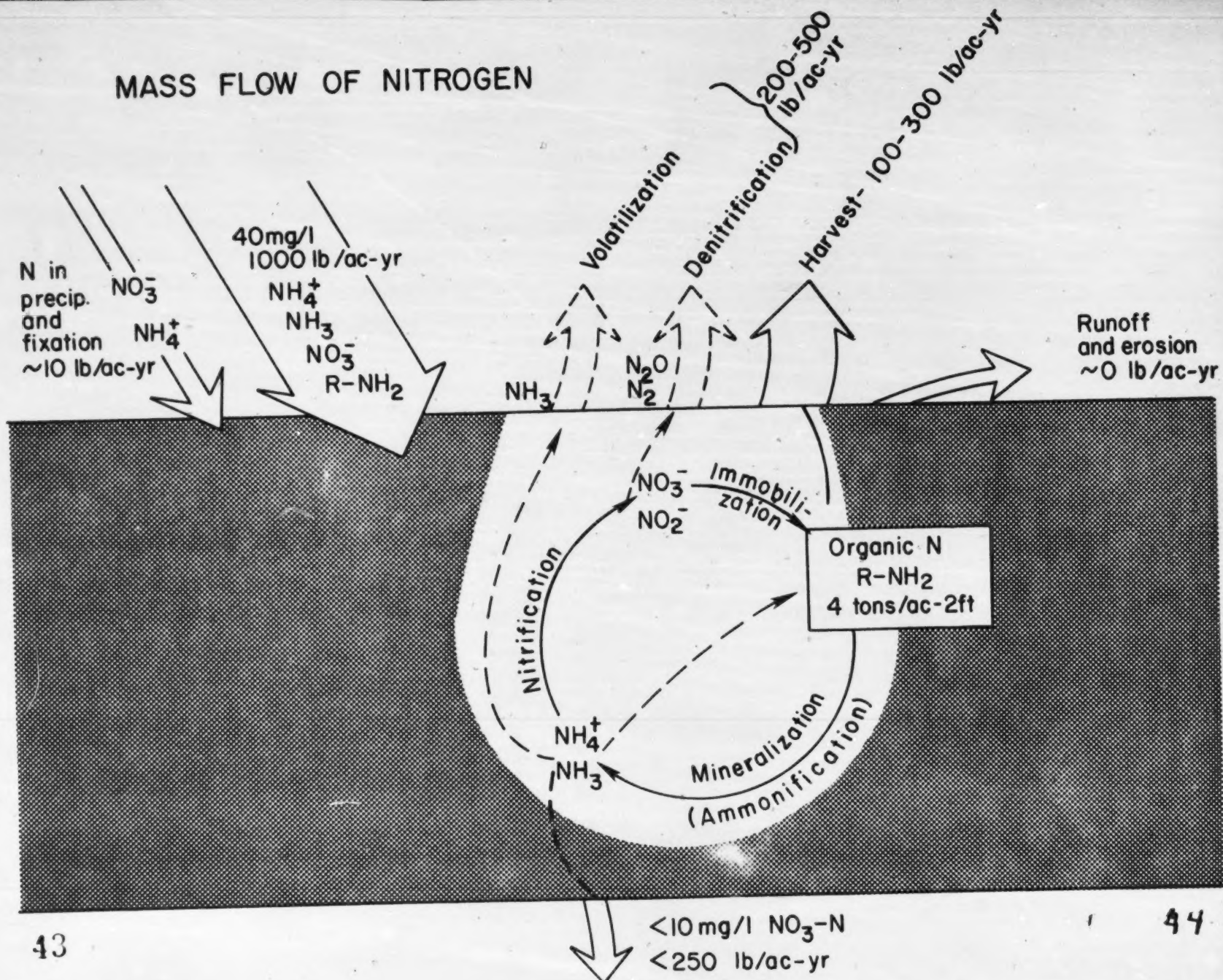


Figure 4. Initial sludge applications may result in a short-term accumulation of organic-N in the soil. In order to compensate for subsequent increased mineralization, successive sludge applications must be reduced until a new equilibrium is established. The amount of reduction depends on the content and form of waste nitrogen, the method of application, and the organic-N decay series (here assumed to be 0.10, 0.05). A = all ammonia nitrogen volatilized during storage and surface application of sludge; B = no ammonia loss, application by soil injection (after Brown, 1975).

MASS FLOW OF NITROGEN



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NITROGEN CONSIDERATIONS

Objectives

At the end of this module, the participant should be able to:

1. Indicate the drinking water standard for $\text{NO}_3\text{-N}$.
2. Indicate the six forms of nitrogen that are of importance in land treatment.
 - a. indicate which are in gaseous form
 - b. indicate which one(s) are generally leached
 - c. indicate which one(s) are tied up by the cation exchange complex.
3. Indicate the three sources of nitrogen input to a land treatment site.
4. Indicate the transformations that the ammonium ion undergoes so it ends up being taken up by the plant.
5. Indicate the mechanisms of nitrogen removal and losses from a land treatment system and the conditions necessary for each mechanism.
6. Indicate a conservative loading rate for wastewater and for sludge according to the nitrogen level of the applied material.
7. Indicate the predominant mechanisms for treating nitrogen in an irrigation system, an overland flow system, and a rapid infiltration system.

RETURN TO LESSON PACKAGE

Script to Accompany the A-T

NITROGEN CONSIDERATIONS

Module 15

January, 1978

NITROGEN CONSIDERATIONS

This lesson concerns the generally most important factor limiting the land application of wastes (Slide 1). This factor is the amount of nitrogen contained in and released from wastewater and sludges. While the inputs of nitrogen can stimulate plant growth, an excess can lead to increased losses to groundwater and eventually to surface waters. This can lead to the results shown in Slide 2. Slide 3 indicates the consequences of too much nitrogen in a water supply. Notice that the drinking water standard is 10 mg/l of nitrate nitrogen. In the past twenty years there have been several hundred cases of methemoglobineamea in the United States with infant death often the result. Many of these cases could be traced to excess nitrate in drinking water. Management decisions, therefore, on nitrogen loading rates must be based on a thorough knowledge of the various forms of nitrogen contained in wastes, their properties, the transformations which occur in soils, and the rates associated with these transformations. The objectives for this lesson are located in an envelope that was with this tape. Find the envelope labelled "Objectives" (Slide 4). Stop the tape recorder and study the objectives. You may keep the objectives for reference during this lesson.

There are six major forms of nitrogen of importance in waste management. Slide 5 indicates the six forms. Slide 6 indicates the levels of organic nitrogen in areas that are of concern to this lesson. Notice that there are about four tons per acre two feet of organic nitrogen tied up in the average soil. This nitrogen is tied up in the humus and is not readily available for direct plant uptake. It is slowly transformed to available forms by means of microbial decomposition. The nitrogen containing organic compounds are often abbreviated $R-NH_2$, as in Slide 6.

Ammoniacal nitrogen, as indicated in Slide 7, includes the ammonium ion and gaseous ammonia. Ammonium nitrogen is the main nitrogen form found in primary-treated sewage. Notice that the ammonium ion has a net positive charge and can thus be held on the cation exchange sites of clay and organic material. Ammonium is also utilized by plants and microorganisms as a nitrogen source. Ammonia gas exists in equilibrium with the ammonium ion.

At pH values greater than about 8.5 ammonia predominates and may escape into the atmosphere in significant quantities.

Nitrite, Slide 8, is a highly mobile anion formed in soils as an intermediate during the microbial conversion of ammonium to nitrate. Nitrite is generally transitory in soils but may accumulate under certain conditions; it is toxic to higher plants in very small quantities.

Nitrate, indicated in Slide 9, is also a highly mobile anion that is the main source of nitrogen for higher plants and microorganisms. It is the main nitrogen constituent of wastewater that has received secondary conventional treatment. Nitrate is of primary interest in waste application systems since it may be readily leached from the soil. When present in excess in drinking water, nitrate can present a health hazard to humans. The drinking water standard for nitrate nitrogen is 10 mg/l. The term $\text{NO}_3\text{-N}$ is read nitrate-nitrogen and refers only to the nitrogen portion of the nitrate anion. Do not confuse nitrate (NO_3^-) with nitrate nitrogen ($\text{NO}_3\text{-N}$) as they are separate entities. Slide 9 indicates the differences between the equivalents of nitrate and nitrate nitrogen.

Nitrous oxide as indicated in Slide 10 is a gaseous form only slightly soluble in water. It is a normal constituent of the atmosphere in small quantities and is probably not utilized by plants. Nitrous oxide is now thought to be damaging the ozone layer that surrounds the earth. It is formed during the denitrification of nitrate.

The final form of nitrogen of importance to land treatment of waste is molecular nitrogen. Notice in Slide 11 that molecular nitrogen makes up most of the normal atmosphere. Molecular nitrogen from the atmosphere is used by nitrogen fixing bacteria associated with leguminous plants. Like nitrous oxide, molecular nitrogen is an end product of denitrification.

Slide 12 indicates a general mass flow diagram for the various forms of nitrogen that are of interest in land application. These forms are interconnected through a series of complex transformations, which collectively constitute the nitrogen cycle. For purposes of this lesson, the nitrogen cycle will be divided into three portions as indicated in the Slide. These portions are the inputs, transformations, and losses or removals. There

are several copies of Slide 12 in an envelope labelled "Mass Flow of Nitrogen" (Slide 13). Find the envelope and take out a copy of the slide. This mass flow diagram will be helpful for reference throughout the lesson.

The inputs of nitrogen can come from three sources as indicated in Slide 14. These are wastewater and/or sludge applications, natural precipitation, and through fixation of molecular nitrogen from the atmosphere by specialized microorganisms. Each of these inputs will be discussed separately.

Municipal wastewaters and sludges contain variable amounts of nitrogen in the forms of organic N, ammonium-N and nitrate-N. Slide 15 indicates some representative values and common loading rates for nitrogen. In several instances there is more nitrogen being added to the soil than can be harvested in a crop. In a situation where this is the case strict nitrogen control would require management practices that maximize nitrogen retention, volatilization, and denitrification if the groundwater standards are to be maintained.

Slide 16 summarizes the annual additions of nitrogen in precipitation. The amounts fluctuate markedly depending upon season, climate, and surrounding industrial activity. Within the U.S. precipitation inputs vary from 1-15 lbs. nitrogen per acre per year.

The last input of nitrogen is brought about by the activity of specialized bacteria which develop in the roots of legumes and certain other plants. These bacteria are capable of fixing atmospheric nitrogen into a form useable by plants. As indicated in Slide 17 this process, called nitrogen fixation, can result in up to 260 lb/N/ac-yr being made available for use by plants. There is evidence, however, that nitrogen fixation is much reduced by the presence of available nitrogen from other sources such as waste additions. This input may, therefore, be an insignificant source of nitrogen on land receiving waste.

We have been discussing the inputs and sources of nitrogen as it relates to land application. Once the nitrogen is applied to the site it undergoes a series of transformations (Slide 18). These transformations will be the focus of the next part of this lesson.

Slide 19 indicates the amounts of nitrogen found in typical mineral soils. The percentage ranges from 0.02 to 0.05 percent. Most of this nitrogen is concentrated in the surface layers and is tied up in organic forms in the humus. It is neither available for use by plants nor for leaching. As can be seen in Slide 20, or in the mass flow diagram, which you should have, decomposition of organic matter by soil microorganisms slowly transforms organic¹N to inorganic forms, a process termed mineralization. The ammonia can then be oxidized to nitrate by nitrification or transformed back into organic form. The transformation from inorganic to organic forms is called immobilization.

We will discuss mineralization first. The general term mineralization covers a whole series of reactions, the end product of which is ammonia or an ammonia compound.

Slide 21 indicates the general form of this reaction. This reaction can be carried out by a wide variety of microorganisms.

Within the pH range of most soils the ammonium ion predominates and, is retained in the soil as shown in Slide 22. Because of competition from other cations and because of the limited nature of the cation exchange capacity, only a limited amount of ammonium can be retained in this way. Ammonium, however, undergoes a further transformation, nitrification, which essentially regenerates the capability of the soil to adsorb ammonium ions.

Nitrification is carried out in two steps by specialized microorganisms. Slide 23 indicates the two steps. Both steps require oxygen and are thus favored in well aerated soils. Nitrification is also affected by temperature, soil moisture and pH. At temperatures near freezing, nitrification essentially stops; the optimum temperature range is between 80 and 90°F. The process is inhibited in very wet or very dry soils and is greatest in neutral to slightly alkaline soils.

Under most conditions favoring the two reactions, step 2, the conversion to nitrate, closely follows step 1. Under conditions indicated in Slide 24, nitrate production could be inhibited, resulting in a temporary build-up of nitrite from the step 1 reaction. Such an accumulation is

serious since nitrite is very toxic to higher plants. With proper conditions, however, nitrification occurs very rapidly. Nitrate-nitrogen generation rates of from 6-22 lbs/ac-day have been reported in surface soil after the addition of 100 lbs/acre of ammonium nitrogen.

The major significance of nitrification for waste application systems lies in the fact that a relatively immobile form is transformed into a highly mobile form (NO_3^-), which may then be readily leached from the soil (Slide 25). Furthermore, nitrate is required for denitrification, a process to be discussed later.

Immobilization is essentially the reverse of mineralization (Slide 26). In this process inorganic nitrogen is converted into organic nitrogen as a component of microbial or plant tissue. Immobilization occurs when the nitrogen content of decomposing organic material is either insufficient or in the wrong form to supply microbial needs. Inorganic nitrogen from the soil is incorporated into the microbial cells and the higher plants.

Slide 27 indicates the effect the carbon:nitrogen ratio has on the determination of whether mineralization or immobilization will predominate. When materials with a high C:N ratio are added to soil, immobilization occurs until the C:N ratio is lowered through the loss of carbon in carbon dioxide. When the C:N ratio approaches 20 or 25, mineralization begins to predominate. When the added organic matter has a low C:N ratio, mineralization occurs from the outset.

Slide 28 summarizes the transformations that have been discussed in this lesson. The rest of the lesson is going to discuss losses and methods of keeping the yellow arrow in the slide from indicating more than 10 mg/l.

The mass flow diagram indicates a few sources of nitrogen losses from a land application site (Slide 29). These are ammonia volatilization, denitrification, crop harvest, and leaching. Surface runoff is also another potential source of nitrogen loss from a site, but this should not be a factor in a well managed land treatment system.

Slide 30 indicates the conditions that favor ammonia volatilization. With dairy manure, under favorable conditions, up to 100% of the ammonia is

lost through volatilization. Surface applications of liquid sludge have resulted in 60% or more of the ammonia-nitrogen being volatilized. Because of problems associated with excess atmospheric ammonia, such as acid rain and offensive odors, volatilization as a nitrogen sink should be considered with caution (Slide 31). These considerations include the density of the population around the site, the prevailing wind and weather conditions, and the size of the buffer zone around the site.

Denitrification, a second source of nitrogen loss from a land application site, is a process whereby nitrate-nitrogen is converted into gaseous forms, either nitrous oxide or molecular nitrogen. Slide 32 indicates the general order of this reaction. As the slide indicates, the reaction may be purely chemical or brought about by microorganisms. Chemodenitrification is usually restricted to acid soils and will be generally of little consequence in land application systems.

Slide 33 indicates conditions that favor biodenitrification. Under anaerobic conditions bacteria use the chemically combined oxygen in nitrate. Nitrous oxide generally predominates under field conditions. The bacteria involved in these reactions require organic carbon as an energy source. Thus to encourage biodenitrification, land application systems must be managed so as to bring nitrate and organic carbon together under anaerobic conditions. This is no simple task.

Sewage effluents, as indicated in Slide 34, contain most of their total nitrogen in organic or ammoniacal forms. Transformation of these forms to nitrate requires aerobic conditions, which are not favorable for denitrification. Thus alternate aerobic and anaerobic periods or zones must be achieved for denitrification. Moreover, when secondary effluents are used in land application, the relative amounts of total N and biodegradable organic carbon are of the same general magnitude, 20 to 30 mg/l (Slide 35). The loss of carbon as CO_2 , however, often occurs at a higher rate than nitrification. This results in organic carbon removal prior to the formation of appreciable nitrate if the mineralization has not run to completion in secondary treatment. Thus, by the time an appreciable amount of nitrogen has been converted to a

form that can be denitrified, much of the required organic carbon has been consumed. Approximately 0.9 to 1.3 grams of biodegradable organic carbon are needed to denitrify one gram of nitrate-nitrogen. This is often not available when secondarily treated effluents are used. For these reasons, the extent of denitrification is extremely difficult to predict and generalized values are often of minimal value without on-site demonstrations using specific waste.

Crop uptake and harvest constitutes a significant mechanism for nitrogen removal. Slide 36 indicates some representative values. In order to be most effective as a nitrogen sink the crop must be harvested (Slide 37). Harvest must be timed to maximize nutrient uptake and to derive the highest economic gain from the crop. Without harvest most of the annual nitrogen uptake will return to the soil as organic nitrogen along with the nitrogen in the roots and litter left after harvest (Slide 38). This organic nitrogen can build up in a soil, especially one that is deficient in humus. It is slowly released through mineralization.

Another way that nitrogen may be more or less permanently tied up in the soil is by adsorption in the humus itself. This reaction has been effectively demonstrated in the laboratory and may account for large amounts of ammonia being stored in the soil in a form that makes it unavailable for other reactions. As Slide 39 indicates this reaction almost increases linearly at a pH above 7 and is directly dependent upon the amount of carbon, that is humus, in the soil. The dependence on the carbon percentage is indicated in Slide 40. Slide 41 indicates the theoretical possibilities of this process. It is suggested that one foot of soil could tie up the ammonia nitrogen in twenty-four feet of secondary effluent when the level of that nitrogen is 25 mg/l. This is for each 1% organic matter in the soil. This is an interesting theory that has been extensively tested in the laboratory. It could explain the tying up of nitrogen in some land treatment systems over and above that which would be expected through immobilization.

Slide 42 indicates the buildup of nitrogen in surface layers of a soil after many years of application. This buildup of nitrogen could be either through immobilization or adsorption in the humus.

The last source of loss of nitrogen from a land application site to be discussed is leaching. Inputs of wastewater or sludge need not result in excessive leaching loss of nitrogen where sound management is practiced. Obviously, where nitrogen inputs exceed the capacity for immobilization, crop uptake, and denitrification, leaching must be expected. Slide 43 indicates the removal efficiency of nitrogen in the water treated at several land application sites. Careful assessment of nitrogen inputs versus estimated losses and removals can limit nitrate leaching to acceptable levels.

This lesson has indicated the inputs, the transformations, and the losses of nitrogen in a land application system. This section discusses the determination of nitrogen loading for both wastewater and for sludge. In any land application system, nitrogen additions must be balanced against acceptable losses and removals (Slide 44). Estimates of inputs and losses are thus required, and must be assessed on both a short and long term basis.

A nitrogen mass balance equation for a terrestrial system is presented in Slide 45. Notice that inputs include not only the nitrogen in the waste but also include the nitrogen in the precipitation and that fixed by bacteria. Mineralization must be included in the inputs because it adds to the total available for plant uptake and for leaching. The object, of course, is to maximize the outputs other than leaching, while keeping the other pollutants in mind and maintaining the site in a non-offensive condition. Not all of the terms may be needed in every case nor are all terms now quantifiable for all situations.

In the initial years of operation, waste application may cause a net accumulation of nitrogen in soil organic matter or on soil colloids. As will be seen in a later section this accumulation can be considerable and long term for some systems. Thus not all nitrogen inputs would be accounted for in losses or removals. Net storage from one year, however, could become a potential input the following year (Slide 46). Failure to consider such short term accumulations can lead to an overestimate of permissible loading rates.

A booklet concerning the calculation of nitrogen loading in a land

application site is located in the lesson box. Find the booklet titled "Calculation for Nitrogen Loading" (Slide 47). The formulas used in this booklet assume that any increases in nitrogen storage in the soil are equalled by mineralization. Thus the formulas are quite conservative. The formulas also do not consider fixation of atmospheric nitrogen, thus a non-leguminous crop is considered. The mass balance equation thus reduces to the one indicated in Slide 48.

After studying the booklet the lesson will continue with case studies indicating experience with nitrogen in existing land treatment systems and additional methods of controlling nitrogen. Be sure to turn the recorder back on after studying the booklet (Slide 49). Stop the recorder and study the booklet.

The final portion of this lesson concerns experience that existing land application systems have had with the treatment of nitrogen. Wastewater irrigation systems, such as in Slide 50, have commonly used application rates ranging from one to three acre-inches per week. With secondary effluents, corresponding quantities of nitrogen are of the same general magnitude as crop requirements over the growing season. Under these application rates, only small amounts of nitrogen are lost through leaching.

Slide 51 indicates a partial nitrogen mass balance for six years of operation of a spray field under hay cover. Nearly all of the applied nitrogen can be accounted for in the harvested reed canary grass. When crop removals and estimated leaching losses are combined, however, they exceed the nitrogen content of applied wastewater. The excess presumably resulted from inputs other than the waste, probably much of it due to mineralization of native organic matter.

An even more interesting case can be obtained from the results of the Werribee Farm land application system serving metropolitan Melbourne, Australia. This system has been in operation for over 75 years. The irrigation system uses raw wastewater containing over 65 mg/l of nitrogen. Every 18-20 days the fields are flooded with an average of 4 inches of this strong wastewater, like in Slide 52. Because the pasture grasses in these fields are grazed by cattle and sheep the amount of nitrogen removed in the crop is not known. The pasture grasses do contain two to three times the nitrogen

found in similar pasture grasses that were not irrigated. This has not resulted in any harm to the grazing herds. A partial mass balance for nitrogen is shown in Slide 53. Notice that even with the very large amount of nitrogen in the wastewater less than fifty pounds per acre of nitrogen leaches through the soil. This is an efficiency of greater than 90% removal and results in an effluent of less than 6 mg/l nitrate-nitrogen. Notice also more than one hundred pounds of nitrogen per acre year has accumulated in the soil. This is for the top acre six inches and for a period of forty-eight years beginning over twenty years after the operation began. Apparently equilibrium of immobilization and mineralization has not yet been reached. Slide 54 indicates conditions at Werribee that probably contribute to the high degree of renovation over the period of the systems operation. The use of untreated waste may have helped by providing enough carbon to maximize denitrification. The temporary flooding could have contributed heavily to ammonia volatilization. This system indicates the long term possibilities of treating raw municipal wastewater resulting in a nitrogen level that meets drinking water standards.

Overland flow systems, like the one diagrammed in Slide 55, usually have nitrogen loadings comparable to irrigation systems. The principal mechanisms for nitrogen removal include crop removal and denitrification, often followed by dilution upon discharge into surface waters. Although renovation efficiencies are typically high, overland flow offers a unique advantage. Since the runoff is usually collected after treatment, it can be analyzed and recycled if it does not meet standards.

Slide 56 shows results for the year-round application of raw comminuted sewage at Ada, Oklahoma. The data do not allow construction of a mass balance although on a concentration basis nitrogen renovation percentages are quite high. Notice that there was a decrease in overall removal efficiency during the winter. This is most likely due to decreased rates of nitrification and denitrification as well as the reduction in plant requirements.

Rapid infiltration systems (Slide 57) generally utilize high rates of wastewater application with the major portion of the effluent moving to

groundwater at some depth or distance. To the extent that nitrogen renovation occurs before entering groundwater, it must be due chiefly to denitrification since nitrogen additions often far exceed crop requirements. Additional apparent renovation results from dilution in the groundwater.

Slide 58 indicates the wastewater and nitrogen loading at a system in Lake George, New York. Nitrogen renovation varies considerably depending on sampling location and season. Winter values, in shallow wells, show high concentrations of up to 21 mg/l in the immediate vicinity of the site. In a seepage area a short distance from the site, however, nitrate-nitrogen concentrations fall to levels below 10 mg/l at all seasons.

Oftentimes in a rapid infiltration system, peaks of nitrate-nitrogen in the effluent are recorded. Slide 59 indicates those peaks at the Flushing Meadows system near Phoenix, Arizona. Apparently, added ammonium was retained in the surface soil by cation exchange reaction during the wetting period. The ammonium was then nitrified during the drying period and flushed into the groundwater early in the next flooding cycle. As the alternate two week cycles were continued, however, ammonium concentration in the percolating water gradually increased while nitrate behavior remained unchanged. Apparently incomplete nitrification during drying cycles led to a gradual ammonium saturation of the cation exchange complex. A look at Slide 60 indicating the loadings to the site indicates one alternative which is to lower the loading. Another suggestion has been that the two week wetting-drying cycles should be periodically alternated with shorter cycles of about two days each, to increase aerobic conditions and rejuvenate the exchange sites for more ammonium retention. A third alternative is to include a long rest period of several weeks to allow complete drying of the upper soil layers.

The reason why this lesson dwells on these pulses of nitrate leaching is because they present interesting management possibilities. Slide 61 indicates one of the possibilities in graph form. Winter application of ammonified effluent could result in efficient removal of nitrogen, in northern areas, as long as the adsorption capacity of the soil is not exceeded. In the spring, when warmer temperatures promote biological nitrification, periodic high nitrate concentrations in the soil leachate should be expected. Essentially, the

original wastewater nitrogen has been concentrated in a relatively small volume of leachate. This leachate could be easily collected and recycled back through the system or used, even sold, as high nitrate fertilizer for crop irrigation. It would be available in the spring when crop nitrogen demand is high. Slide 62 illustrates these possibilities.

Slide 63 is a diagram of the last system that will be considered in this lesson. This experimental system, called the Barriered Landscape Water Renovation System is being tested at Michigan State University. It consists of a mound of soil underlain by an impervious polyvinyl water barrier. The thin bed of limestone or slag on top of the mound removes phosphorus. The aerobic zone allows for organic matter decomposition and nitrification of ammonium. The downward movement of nitrified effluent, however, is stopped by the impervious barrier and forced to move laterally in the anaerobic zone immediately above the barrier. Denitrification in this zone is stimulated by adding a readily degradable carbon source such as crushed grain. Renovated water then moves off the edge of the water barrier and through deeper soil layers to the water table. Such a system can maximize denitrification, even under relatively low wastewater application rates. The nitrogen removal potential was demonstrated with liquid swine waste. Slide 64 indicates the loadings and results. The system remains to be tested for domestic wastewater.

We can close this discussion by referring to the mass flow diagram with which we began this lesson (Slide 65). Nitrogen, in a land application system, is the pollutant that generally is the limiting factor. Although nitrogen is the limiting factor in determining land area for treatment of wastewater, several systems have dealt successfully and cost effectively with nitrogen resulting in treatment efficiency equalling advanced waste treatment techniques.

RETURN TO LESSON PACKAGE

Booklet to Accompany the A-T
NITROGEN CONSIDERATIONS
Calculation for Nitrogen Loading
Module 15
January, 1978

Booklet to Accompany Nitrogen Considerations

Audio-tutorial lesson

Calculation of Nitrogen Loading

The calculation of an acceptable Nitrogen Loading rate is accomplished by forming a mass balance equation. Shown below are the inputs and removals of a land application system as was shown in slide 45.

N in Waste + N in Precipitation + N Fixation + Mineralization of Native Organic N =
N Removal in Crops + N Lost by Leaching and Runoff + Denitrification + Ammonia
Volatilization + N Accumulation in Soil

Over the long term site life a dynamic equilibrium will be established between the mineralization of organic N in the soil and accumulation of N in the soil. A non-leguminous crop should be grown to effectively reduce N fixation to zero. With these conditions in effect, long term equilibrium and a non-leguminous crop, the mass balance equation will reduce to:

Total N in waste + N in precip = N removal by crops + leaching or
runoff losses + N lost by denitrification + N lost

This can be mathematically expressed as:

$$N + \frac{cP}{4.43} = C + \frac{aQ}{4.43} + dN + vN \quad (1)$$

Where:

N = total nitrogen in applied wastes (lb/acre yr)

c = concentration of nitrogen in precipitation (mg/l)

P = Precipitation (acre in/acre yr)

C = removal of nitrogen in the crop (lb/acre yr)

a = allowable nitrogen concentration in water leaving the site (mg/l)

Q = value of water leaving the site through percolation or runoff (acre in/acre yr)

d = fraction of N which is denitrified (%/100)

v = fraction of N which is volatilized as ammonia (%/100)

4.43 = conversion factor

This equation can be put in a more useful form for determining wastewater loading by equating Q with the inflows and outflows of the system, thus:

$$Q = P + W - ET$$

where W = wastewater additions acre in/acre yr

ET = evapotranspiration acre in/acre yr

and by equating N, total nitrogen in applied wastes, with the concentration of nitrogen in the wastewater and the amount of wastewater applied, thus:

$$N = \frac{yW}{4.43} \quad (2)$$

where y = concentration of total nitrogen in the waste applied mg/l

Making these changes puts the mass balance equation in the Form:

$$\frac{yW}{4.43} + \frac{cP}{4.43} = \frac{a(p + W - ET)}{4.43} + \frac{d(yW)}{4.43} + \frac{v(yW)}{v.42} \quad (3)$$

Solving this equation for W , wastewater application yields:

$$W = \frac{4.43 + a(P - ET) - cP}{y - a - y(d+v)} \quad (4)$$

The wastewater applications obtained by this equation are only as accurate as the quantities which were used in the equation. Crop removal, precipitation, and evapotranspiration are averages and will vary from year to year, as well as seasonally. This variation will cause the water exiting the site at times to contain more or at times less nitrogen than the allowable concentration. The amount of volatilization and denitrification of the nitrogen is hard to determine accurately. Conservative estimates of zero should be used for the amount volatilized and denitrified, unless on-site demonstrations or research indicate otherwise. Conservative estimates of volatilization and denitrification would help to keep the concentration of N in the wastewater below the allowable concentration.

Problem #1

Determine a) the wastewater application, b) the weekly liquid loading rate, c) the acreage required and d) the lbs of N applied per year given the following information. The site is for a small town in the Northeastern United States which will need treatment for 1.5 mgd of wastewater containing 35 mg/l nitrogen. The annual average precipitation is 34 inches which contains .4 mg/l N. Reed canary grass is the proposed crop to be grown. Sample plots showed 325 lbs N uptake per year. Estimated evapotranspiration for reed canary grass at this site is 28 inches/yr. The application period will be 36 weeks. Denitrification and volatilization were conservatively estimated at 10% of the applied Nitrogen from studies of the sample. The allowable nitrogen concentration in the treated water will be 10 mg/l which is the U.S. Public Health Service standard for drinking water.

Problem #2

Determine the quantities required in Problem #1 for a 1.5 mgd flow with 20 mg/l N. The average annual precipitation is 29 inches with .8 mg/l N. The crop uptake will be assumed to be 300 lbs Nitrogen/yr with evapotranspiration at 28 inches/yr. The application period will be for 30 weeks. Denitrification and volatilization will be assumed to be zero for conservative design. The U.S. Public Health Service drinking water standard of 10 mg/l will be the allowable concentration of N in the treated water.

Solution to problem #1

a) using equation (4) $W = \frac{4.43C + a(P-ET) - cP}{y-a-y(d+v)}$

and from the given information:

$$W = \frac{4.43 (325) + 10 (34-28) - .4(34)}{35 - 10 - 35 (.1)}$$

$$W = 69.1 \text{ inches/yr}$$

- b) by dividing the wastewater application by the number of weeks of application per year the application per week can be obtained:

$$\frac{69.1 \text{ inches/yr}}{36 \text{ weeks/yr}} = 1.9 \text{ inches/wk}$$

- c) converting the daily flow rate to acre inches and then dividing by the inches applied will give the acres required:

$$\begin{aligned} \text{acre inches applied} &= 1.5 \text{ Mg/day} \times 365 \text{ days/yr} \times 3.067 \frac{\text{acre ft}}{\text{mg}} \times \frac{12 \text{ inches}}{\text{ft}} \\ &= 20150.19 \text{ acre inches/yr} \end{aligned}$$

$$\frac{20150.19 \text{ acre inches/yr}}{69.1 \text{ inches/yr}} = 291.6 \text{ acres}$$

d) using equation (2) $N = \frac{yW}{4.43}$

substituting into the equation $N = \frac{(35) 69.1}{4.43} = 546 \text{ lbs N/acre yr}$

Solution to Problem #2

a) using equation 4
$$W = \frac{4.43 (300) + 10(29-28) - .8(29)}{20 - 10 - 20 (0)}$$

$$W = 129.6 \text{ inches/yr}$$

b)
$$\frac{129.6 \text{ inches/yr}}{30 \text{ wk/yr}} = 4.32 \text{ inches/wk}$$

c)
$$\text{acre inches applied} = 1.5 \text{ mg/day} \times 365 \frac{\text{days}}{\text{yr}} \times 3.067 \frac{\text{acre ft}}{\text{Mg}} \times \frac{12 \text{ inches}}{\text{feet}}$$

$$= 20150.19 \text{ acre inches/yr}$$

$$\frac{20150.19 \text{ acre inches/yr}}{129.6 \text{ inches/yr}} = 155.5 \text{ acres}$$

d) use equation (2)
$$N = \frac{yW}{4.43} = \frac{20 (129.6)}{4.43} = 585 \text{ lbs N/acre yr}$$

Compare these results with those found from Problem #1. Note that increasing C, a, P and (d + v) will increase the wastewater applied, while increasing ET., c, y, and a will decrease the wastewater applied. Note also that the application rate must be compared with the infiltration rate of the soil to be sure the soil can accept that amount of water.

To use the mass balance equation (1) for calculating the loading rates for sludges, it is convenient to equate Q with the inflows and outflows of the system, thus:

$$Q = P + z W - ET$$

where: z = moisture fraction in liquid sludge (%/100)

W = liquid sludge additions acre-in/acre-yr

ET = evapotranspiration acre-in/acre-yr

and to equate N , with the liquid sludge additions by using the percent total solids and the percent of N in the solids, thus:

$$N = \frac{(t)(s)10^6 W}{4.43} \quad (5)$$

where t = fraction of N in solid waste (%/100)

s = fraction of solids in sludge (5/100)

Making these changes in equation (1) yields:

$$\frac{(t)(s)(10^6)W}{4.43} + \frac{cP}{4.43} = C + \frac{a(P + zW - ET)}{4.43} + \frac{(d)(t)(s)10^6W}{4.43} + \frac{(v)(t)(s)10^6W}{4.43} \quad (6)$$

Solving this equation for liquid sludge application W gives:

$$W = \frac{4.43C + a(P - ET) - cP}{(t)(s)10^6 - (a)(z) - (t)(s)10^6(d + v)} \quad (7)$$

The comments following equation 4 apply to equation (7) as well.

Problem #3

Determine a) the liquid sludge loading, b) the acreage required and c) the lbs of N applied per acre yr for a treatment plant producing 1.2 MG of sludge with 5% solids. The sludge contains 1.5% Nitrogen (dry solids). The average annual precipitation for the area is 33 inches with 0.7 mg N/l. Evapotranspiration is assumed to be 25 inches/yr for a crop which will remove 290 lbs N/yr. The allowable concentration of N leaching through the site is 10 mg/l. These show that at least 10% of the applied Nitrogen will be volatilized or denitrified.

Solution to problem #3

a) using equation (7)

$$W = \frac{4.43 (290) + 10 (33 - 25) - (.7) 33}{(.05) (.015) 10^6 - ((10) .95) - (.05) (.015) 10^6 (.1)}$$

$$W = 2.0 \text{ acre in/acre yr}$$

b) changing 1.2 MG/day to acre in/year and dividing by W will give the acreage required.

$$1.2 \text{ MG/yr} \times \frac{3.067 \text{ acre/ft}}{\text{Mg}} \times \frac{12 \text{ inches}}{\text{ft}} = 44.2 \frac{\text{acre in}}{\text{yr}}$$

$$\frac{44.2 \text{ acre in/yr}}{2.0 \text{ in/yr}} = 22 \text{ acres}$$

c) using equation (5)

$$N = \frac{(.05) (.015) 10^6 (2)}{4.43}$$

$$N = 339 \text{ lbs N/acre yr}$$